Using OP-TEE as a Cryptography Engine

Greg Malysa

Timesys Corporation

Outline

- OP-TEE Background
- Adding Crypto Providers in OP-TEE
  - HW RNG
  - HW Crypto Accelerators
- Using OP-TEE Crypto From Linux
  - Using a Custom Library
  - System Integration
  - Standard Solutions

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The Internet of Things is Here

Everything is connected now

- Smart Fridges
- Smart TVs
- Industrial/SCADA systems
- Connected medical systems
- In-car networking
- ...

Need to store secret or immutable data: certificates, keys, hashes

How Do We Store Things Securely?

- Hardware Security Module (HSM)
- Trusted Platform Module (TPM)
- Other hardware-based Secure Elements
- On-die Secure Enclaves
- ARM TrustZone

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SoC Security Features

On-die Security Features:

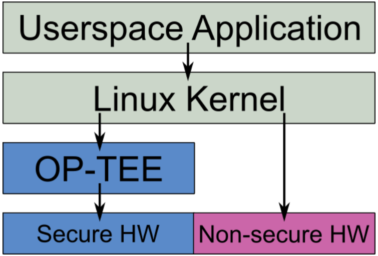
- Tamper-resistant/Secure OTP (SOTP) memory
- Transparent DRAM encryption
- Cryptographic accelerators (e.g. NXP CAAM)

ARM TrustZone:

- Secure Boot
- Secure/non-secure processor states
- Hardware isolation by state
- Secure Monitor Call to request secure action

What is OP-TEE?

The **O**pen **P**ortable **T**rusted **E**xecution **E**nvironment.



OP-TEE is built on ARM TrustZone

Why TEE?

- GlobalPlatform specification
- Trusted Applications can run on any TEE
- Linux supports OP-TEE and AMD-TEE
- Secure API Features
  - Encrypted persistent storage
  - Cryptography routines
  - Private data not accessible outside Trusted Application
- Using a TEE offers protection against 0days in kernel, userspace

Outline

OP-TEE New Platform Bring-up

- Basic platform bringup, booting, running
- Hardware RNG
- Hardware cryptography accelerators
- SOTP and secure peripherals

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Background

Assume some familiarity with

- `core/arch/arm/plat-X/conf.mk`
  - Build configuration and options
  - Controls which features are included in the build
  - Uses make syntax
- `core/arch/arm/plat-X/platform_config.h`
  - Platform specific constants, typically memory layout configuration
  - Regular C header file
- `sub.mk`
  - There's one in every folder
  - Controls which files are built by adding to `srcs-y`
  - Uses make syntax

RNG Driver Plan

- Understand the crypto RNG API
- Implement driver to match
- Configure build to use driver

Crypto RNG API

- The OP-TEE crypto-rng API is only three functions:

```
TEE_Result crypto_rng_init(const void *data, size_t dlen);

TEE_Result crypto_rng_add_event(enum crypto_rng_src sid,
    unsigned int *pnum, const void *data, size_t dlen);

TEE_Result crypto_rng_read(void *buf, size_t blen);
```

- `rng_hw.c` provides `__weak`-linked defaults!
- `crypto_rng_read()` default calls `hw_get_random_byte()`

Basic Driver Implementation

```
#define HW_RNG_CONTROL 0x00000000
#define HW_RNG_DATA    0x00000004
static vaddr_t hwrng_addr = 0;

TEE_Result crypto_rng_init(const void *data, size_t dlen) {
  hwrng_addr = core_mmu_get_va(HW_RNG_BASE, MEM_AREA_IO_SEC);

  if (!hwrng_addr)
    return TEE_ERROR_GENERIC;

  return TEE_SUCCESS;
}

uint8_t hw_get_random_byte() {
  return io_read8(hwrng_addr + HW_RNG_DATA);
}
```

Configuration

In `platform_config.h`, define hardware addresses

```
#define HW_RNG_BASE     0x00001000
#define HW_RNG_SIZE     0x0000000C
```

In `conf.mk`, disable the Fortuna PRNG (automatically enabling HW support), and enable new hardware driver

```
$(call force,CFG_WITH_SOFTWARE_PRNG,n)
CFG_MY_HW_RNG := y
```

In `sub.mk`, include new driver based on config

```
srcs-$(CFG_MY_HW_RNG) += my_hwrng.c
```

In `main.c`, register HW RNG's memory and restrict it to the secure state

```
register_phys_mem_pgdir(MEM_AREA_IO_SEC, HW_RNG_BASE, HW_RNG_SIZE);
```

HW Crypto Accelerators

Start with the internal crypto API, `core/crypto/crypto.c`

- skcipher, hash, mac all work one way
- akcipher works differently

Hash/mac/skcipher lifecycle:

crypto_hash_ops

crypto_hash_* API uses an ops struct to perform operations

```
struct crypto_hash_ops {
  TEE_Result (*init)(...);
  TEE_Result (*update)(...);
  TEE_Result (*final)(...);
  void (*free_ctx)(...);
  void (*copy_state)(...);
};
```

Define new ops struct for HW accelerator and connect it!

Life-cycle Operations in crypto_hash_ops

Compare hash life-cycle to `crypto_hash_ops`

No alloc function in `crypto_hash_ops`

Peek into alloc

```
TEE_Result crypto_hash_alloc_ctx(void **ctx, uint32_t algo) {
  TEE_Result res = TEE_ERROR_NOT_IMPLEMENTED;
  struct crypto_hash_ctx *c = NULL;
  /*
   * Use default cryptographic implementation if no matching
   * drvcrypt device.
   */
  res = drvcrypt_hash_alloc_ctx(&c, algo);
  if (res == TEE_ERROR_NOT_IMPLEMENTED) {
    switch (algo) {
    case TEE_ALG_MD5:
      res = crypto_md5_alloc_ctx(&c);
      break;
      // .. more hash alg cases
    }
  }
  // ... error checking and result
}
```

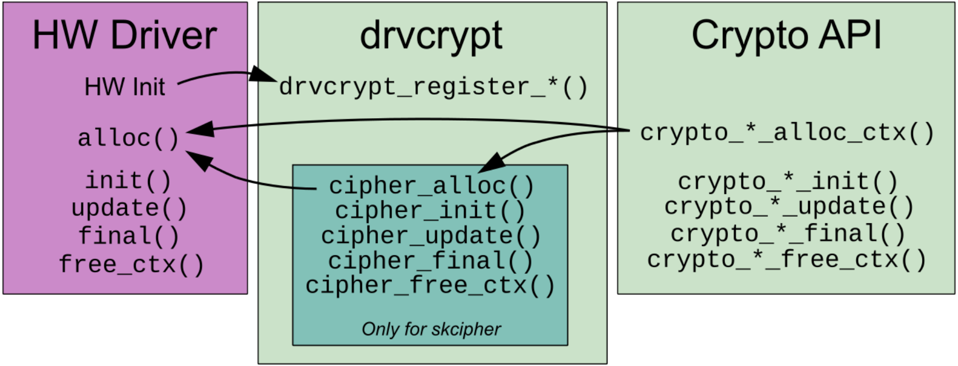
What is drvcrypt?

`drvcrypt` is the interface for integrating hardware accelerators

- Supports one drvcrypt provider for each operation type
- Adding drvcrypt providers requires *no changes* to crypto core
- Some software fallback is automatic
- akcipher (RSA, DSA, ECC, etc.) paths are unique, implement carefully

drvcrypt Flow

We only need to implement the HW driver below



drvcrypt flow

- Do regular HW initialization
- `drvcrypt_register_*` used to register a driver for use
  - hash and mac need 1 function to allocate `crypto_*_ctx`
  - skcipher needs instance of `drvcrypt_cipher`
  - akcipher algorithms have unique structs to register
- Regular crypto API will call hardware-associated routines automatically

Initialization and Registration

```
TEE_Result hw_hash_probe() {
  /*
   * get virtual address of hardware,
   * perform actual hardware initialization,
   * etc. first, then register drvcrypt last
   */
  return drvcrypt_register_hash(hw_hash_alloc);
}

early_init(hw_hash_probe);
```

HW Alloc Implementation

```
TEE_Result hw_hash_alloc(struct crypto_hash_ctx **ctx,
    uint32_t algo) {
  struct *hw_hash_ctx = NULL;

  if (!hw_supports_algo(algo))
    return TEE_ERROR_NOT_IMPLEMENTED;

  // don't forget error checking
  hw_hash_ctx = malloc(sizeof(*hw_hash_ctx));
  hw_hash_ctx->algo = algo;
  hw_hash_ctx->ioaddr = hw_get_free_hw();
  hw_hash_ctx->ctx.ops = &hw_hash_ops;

  // later we use container_of to obtain hw_hash_ctx from
   crypto_hash_ctx
  // just like in the linux kernel
  *ctx = &hw_hash_ctx->ctx
  return TEE_SUCCESS;
}
```

HW Context Struct

```c
struct hw_hash_ctx {
  struct crypto_hash_ctx ctx;
  uint32_t algo;
  vaddr_t ioaddr;
};

// @todo you have to implement all of these functions
static const struct crypto_hash_ops hw_hash_ops = {
  .init = hw_hash_init,
  .update = hw_hash_update,
  .final = hw_hash_final,
  .free_ctx = hw_hash_free,
  .copy_state = hw_hash_copy_state,
};
```

Configuration

- In `conf.mk`, enable drvcrypt

```
$(call force,CFG_CRYPTO_DRIVER,y)
```

- Then, enable sub-drivers for your needs

```
CFG_CRYPTO_DRV_HASH
CFG_CRYPTO_DRV_MAC
CFG_CRYPTO_DRV_CIPHER
CFG_CRYPTO_DRV_ACIPHER
```

- `CFG_CRYPTO_DRV_ACIPHER` has *even more* sub-drivers available
- Add driver to `sub.mk`, configure addresses in `platform_config.h`

Outline

Accessing OP-TEE From Linux

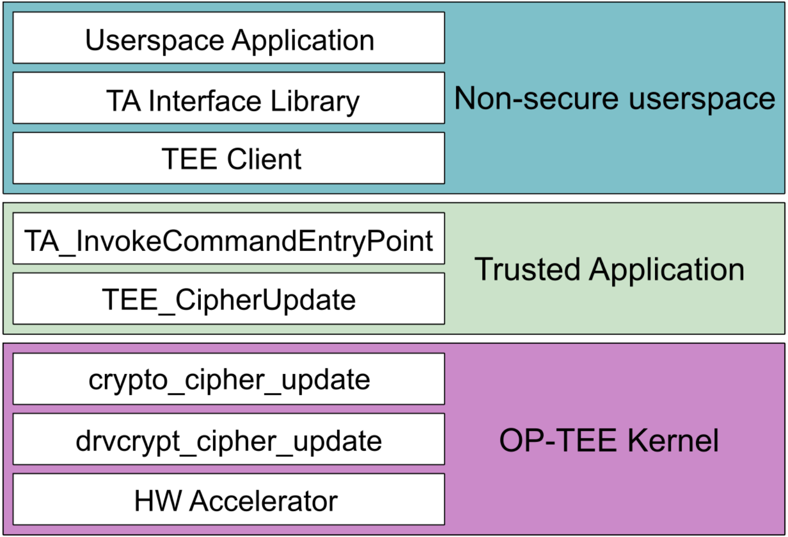
Access options:

- Custom Library
- Linux Kernel Crypto API
- OpenSSL
- PKCS#11

Warning

The code examples to follow are stripped down to highlight specific aspects of the API. They have been stripped to fit on slides and require additional error checking.

Application Flow



Trusted Application

- Trusted Applications (TAs) run in OP-TEE's userspace
- Use GlobalPlatform TEE Internal Core API
  - Cryptography accessed through "Operation" and "Object" opaque handles
- Interface to Linux applications is RPC through shared memory

What is a TEE Operation?

TEE Operations are opaque references to cryptographic operations

- Operation life-cycle is analogous to hash life-cycle earlier
- Operations are associated with keys using TEE Objects
- Operations can represent any type of cryptographic operation

What are TEE Objects?

TEE Objects are opaque references to data managed by OP-TEE

- 2 flavors of object: Persistent and Transient
- Transient Objects exist only in RAM and for the lifetime of a TA
  - If the TA panics, these are deleted
  - Must initialize before use
  - Recommend using Transient Objects for cryptographic keys
- Persistent Objects store information encrypted at rest
  - Enable long-term storage of sensitive data
  - Stored encrypted on Linux filesystem or in eMMC RPMB
  - Can be restricted to a single TA or shared between TAs

TA Interface

- Each command is identified by a number
- Each command has up to 4 arguments (in OP-TEE)
- Arguments can be inputs/outputs/both
- Arguments can be a 64-bit scalar or a buffer with fixed length

Minimal TA Interface

```
TEE_Result TA_InvokeCommandEntryPoint(void *session_ctx,
  uint32_t cmd_id, uint32_t param_types,
  TEE_Param params[4]) {

  switch (cmd_id) {
  case CMD_TA_AES_ENCRYPT:
    return TA_EncryptAES(param_types, params);
  case CMD_TA_AES_DECRYPT:
    return TA_DecryptAES(param_types, params);
  default:
    return TEE_ERROR_NOT_SUPPORTED;
  }
}
```

Minimal TA Interface II

```
static TEE_ObjectHandle aeskey;
TEE_Result TA_EncryptAES(uint32_t param_types, TEE_Param params[4])
    {
  const uint32_t exp_param_types = TEE_PARAM_TYPES(
    TEE_PARAM_TYPE_MEMREF_INPUT, // IV
    TEE_PARAM_TYPE_MEMREF_INPUT, // input
    TEE_PARAM_TYPE_MEMREF_OUTPUT, // output
    TEE_PARAM_TYPE_NONE
  );

  if (params != exp_param_types)
    return TEE_ERROR_BAD_PARAMETERS;

  return aes_encrypt(aeskey,
    params[0].memref.buffer, params[0].memref.size,
    params[1].memref.buffer, params[1].memref.size,
    params[2].memref.buffer, &params[2].memref.size);
}
```

Minimal AES code

```
TEE_Result aes_encrypt(TEE_ObjectHandle key, const uint8_t *iv,
  size_t ivlen, const uint8_t *in, size_t inlen,
  uint8_t *out, size_t *outlen) {

  TEE_OperationHandle op;
  TEE_Result res;

  res = TEE_AllocateOperation(&op, TEE_ALG_AES_CBC_NOPAD,
    TEE_MODE_ENCRYPT, 128);
  res = TEE_SetOperationKey(op, key);
  TEE_CipherInit(op, iv, ivlen);
  res = TEE_CipherUpdate(op, in, inlen, out, outlen);
  TEE_FreeOperation(op);
  return res;
}
```

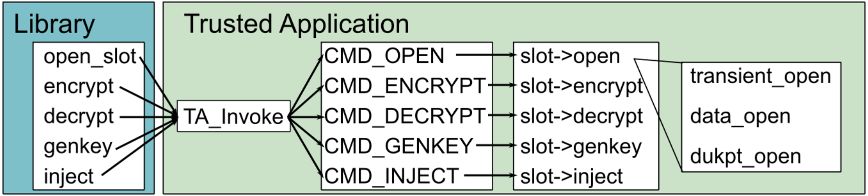
Minimal Example Caveats

- Need to check `res` along the way
- TEE API will **panic** as a safety precaution
- Panic is unrecoverable, do error checking instead!
  - IV length, input and output lengths, block size
- Some other things have been omitted for brevity or to focus on the TEE API

Building a Secure Storage System

- Goal: software-based secure element
- Organize data into slots
- Slots are optionally backed by persistent objects
- Slots support different ops based on type

Storage Application Flow



Slot Ops

```
struct slot_ops {
  // bookkeeping, internal
  TEE_Result (*new)(struct slot *);
  TEE_Result (*init)(struct slot *);
  TEE_Result (*write)(struct slot *);

  // actual operations interface
  TEE_Result (*encrypt)(struct slot *, ...);
  TEE_Result (*decrypt)(struct slot *, ...);
  // ...
};
```

Opening a Slot

```
TEE_Result __open_slot(uint32_t slot) {
  uint32_t flags = TEE_DATA_FLAG_ACCESS_READ |
    TEE_DATA_FLAG_ACCESS_WRITE;
  struct slot *slot = &slots[slot];
  TEE_Result res;

  res = slot->ops->new(slot);
  res = TEE_OpenPersistentObject(TEE_STORAGE_PRIVATE, slot->id,
    strlen(slot->id), flags, &slot->persistent);
  if (!res)
    res = slot->ops->init(slot);
  if (res == TEE_ERROR_ITEM_NOT_FOUND) {
    res = TEE_SUCCESS;
    slot->persistent = TEE_HANDLE_NULL;
  }
  return res;
}
```

slot->write()

```
static uint32_t write_flags = TEE_DATA_FLAG_ACCESS_READ |
    TEE_DATA_FLAG_ACCESS_WRITE | TEE_DATA_FLAG_ACCESS_WRITE_META |
    TEE_DATA_FLAG_OVERWRITE;

TEE_Result transient_write(struct slot *slot) {
  return TEE_CreatePersistentObject(
    TEE_STORAGE_PRIVATE, slot->id, strlen(slot->id), write_flags,
    slot->transient, NULL, 0,
    &slot->persistent);
}

TEE_Result data_write(struct slot *slot) {
  return TEE_CreatePersistentObject(
    TEE_STORAGE_PRIVATE, slot->id, strlen(slot->id), write_flags,
    TEE_HANDLE_NULL, slot->data, slot->length,
    &slot->persistent);
}
```

Remaining TA Pieces

- Routine tasks
  - Fill in ops struct per slot type
  - Fill in switch statement for invoke
  - Do error checking and parameter validation
- One time programming support (for mfg)
- Handle `TEE_ERROR_CORRUPT_OBJECT`

Linux Userspace Access Library

- Library mirrors the invoke structure
  - At least one library function per command
  - Additional library functions for parameterized commands, such as "AES OP" with ENCRYPT or DECRYPT as an argument
- Typical TEE Client-based implementation

Linux Kernel Integration

- Disable HW crypto drivers that are now owned by OP-TEE
- Register new crypto providers with the kernel (sounds familiar)
  - `crypto_register_alg(struct crypto_alg *)`
  - `crypto_register_shash(struct shash_alg *)`
- Overall implementation is analogous to userspace library

struct cipher_alg

```c
struct cipher_alg {
  unsigned int cia_min_keysize;
  unsigned int cia_max_keysize;
  int (*cia_setkey)(struct crypto_tfm *tfm, const u8 *key,
    unsigned int keylen);
  void (*cia_encrypt)(struct crypto_tfm *tfm, u8 *dst,
    const u8 *src);
  void (*cia_decrypt)(struct crypto_tfm *tfm, u8 *dst,
    const u8 *src);
};
```

OpenSSL Integration

- OpenSSL can be extended through custom engines
- An engine could wrap our library
- Easy path to integration?

OpenSSL Integration

- OpenSSL can be extended through custom engines
- An engine could wrap our library
- Easy path to integration?
- **No**
- Consider alternatives:
  - `AF_ALG` and kernel interface
  - Use OpenSC's PKCS#11 wrapper engine, libp11
  - Write PKCS#11 compliant provider

PKCS#11

The PKCS#11 specification has everything we want in key storage:

- Multiple slots for cryptographic objects
- Interface for performing operations on those objects
- Cryptographic data is not exposed to the user
- Cryptoki API also bears some resemblance to TEE APIs

Lots of other applications already work with PKCS#11 providers

pkcs11 TA and libckteec

- OP-TEE team has been working on pkcs11 TA and libckteec
- Not quite ready but very promising
- See Ruchika and Etienne's presentation from LVC21 earlier this year
  - `https://static.linaro.org/connect/lvc21/presentations/lvc21-215.pdf`

fTPM

- Software implementation of TPM
- Microsoft provides an OP-TEE-backed implementation
- Mainline Linux driver available for access
  - https://git.kernel.org/pub/scm/linux/kernel/git/torvalds/linux.git/tree/drivers/char/tpm/tpm_ftpm_tee.c
- Can use directly or plug into PKCS#11 adapter

Summary

- Use OP-TEE to provide cryptographic services
- Add hardware accelerators directly to OP-TEE
- Access those services through Trusted Applications
- Access Trusted Applications through a userspace library
- Be on the look out for pkcs11 and libckteec to avoid rerolling them!

Embedded Linux Conference